An investigation of short translator linear machines for use in a free piston engine

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***Abstract*— In a free piston engine, the translator of a linear generator is coupled directly to the moving cylinder of a thermodynamic engine. For a linear machine to have a constant active area, either the translator or the stator must be oversized. The length of the translator effects its mass, which in turn effects the engine performance. This paper investigates the effect of translator length on the overall power density of a free piston engine coupled to a cylindrical permanent magnet machine.**

Keywords*— *Linear Generator, Free Piston Engine, Alternative Energy

I. Introduction

As part of the drive towards efficient power generation, direct drive free piston engines are being developed by a number of research groups. By developing a linear electrical machine coupled directly to the reciprocating cylinder of a thermodynamic engine, it is possible to design a very low mass generator by the elimination of the crankshaft and all rotary components as proposed by [1], for example. Fully integrating the components with an internal combustion engine should allow for efficient and compact conversion from hydro-carbons into electricity. At small scale, this could be used as an alternative to a conventional reciprocating engine as a range extender in a plug-in hybrid electric vehicle. At larger scale, it can be used to distribute the electricity generation hardware on-board a ship more evenly – moving away from a single large generating unit located in the centre of the hull, and therefore having an impact on the hydrodynamic design of more-electric or hybrid ships. Even more applications are available when using external combustion engines, such as those based on the Sterling or Joule cycle [2], where free piston engines can be used to convert waste heat from any source into electricity. Using a modular approach, if a design is optimised for either efficiency or power density it can be scaled up for any application. Several authors have investigated different electrical machine topologies for this application, such as tubular [3], axial flux [4] and transverse flux [5]. The tubular machine was shown in [6] to be attractive when considering resistive loading, due to its low inductance and relatively simple construction and is hence used in this study.

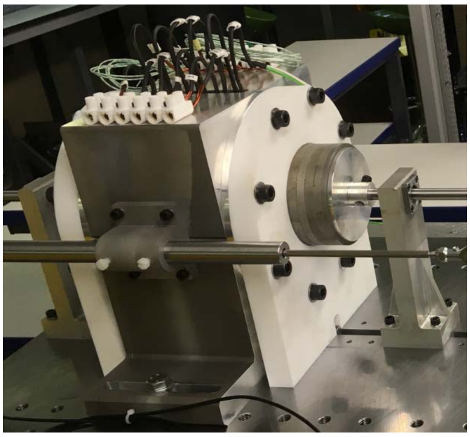

Fig. 1: Tubular linear machine developed for the free piston engine.

For a linear machine to have a constant active area throughout its length, either the translator or stator needs to be oversized by the peak to peak stroke length. In [7], electrical efficiency of the machine and simplicity of assembly were the sole drivers of the design of the tubular machine shown in Fig. 1. The permanent magnet translator was therefore oversized in the axial direction to enable all coils to be active at all times in the cycle. In a fully integrated system, overall system efficiency and cost must be considered.

For a machine where the peak to peak amplitude is equal to the active length, i.e. an amplitude ratio of one, exactly half the magnets are inactive at any position. As the mass of the translator is also the moving mass of the engine, inactive magnets have a big impact on the operating power and efficiency of the engine. If instead the stator is oversized, as proposed elsewhere to facilitate a low mass translator [8], the thermodynamic efficiency and capital cost of the electrical machine both improve, albeit at the expense of some inactive coils.

This paper presents a fully integrated software model of the machine in Fig. 1 coupled to a free piston engine operating on the Joule cycle. The model is used to investigate, from a system perspective, the influence of translator length on free piston engine efficiency.

II. Machine Configuration

The translator consists of axially magnetised magnets separated by soft magnetic pole pieces. The stator has circumferentially wound coils, Fig 2. Manufacture of the long translator version was described in [6]. The active

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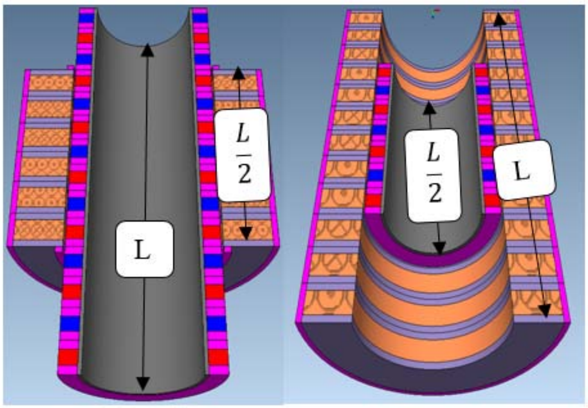

Fig. 2: Comparison of short and long stranslator for scaled modular type design (section II).

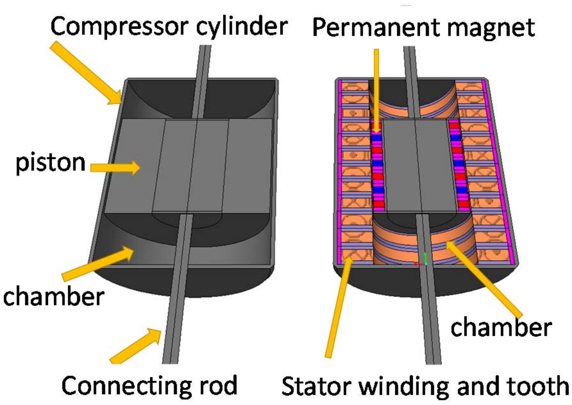

Fig. 3: Integration of electrical machine into free piston engine compressor

electromagnetic area is composed of a three phase, six slot /seven pole combination and equipped with a modular stator winding in which circumferential coils of each phase are located adjacent to each other. The flux path in the stator core back and translator pole pieces is three dimensional and so these components are made from soft magnetic composite material, whereas flux in the stator teeth is radial and circumferential, and so they are formed of axial laminations. The design process has been reported and results validated previously by the authors [9].

The two configurations of the machine considered in this paper, namely the long and short translator versions, are given in Fig 2. Electromagnetically they are almost identical, apart from the end effects experienced by the coils in the long translator model. Identical pole dimensions have been used for both. In Fig. 3, a schematic is provided to clarify how the electrical machine is envisaged to fit within the free piston engine. The shorter translator machine offers considerable space saving and offers the potential of an integrated design. Table I shows the outside dimensions of all the linear machines considered in this paper.

TABLE I. DIMENSIONS OF LINEAR MACHINES USED IN DESIGN STUDY

Parameter		unit
Stator outer diameter	180	mm
Translator outer diameter	103	mm
Active axial length	120	mm
airgap	1.5	mm
Overall axial length	240	mm

III. MODELLING

Fundamental operation and performance of various free piston engines has been simulated and presented by various authors [10-12]. Expansion of this work includes combined electrical and dynamic performance using assorted simulation tools [13], [14] and numerical models [15]. Various investigations on some key engine parameters have been presented in [16-17] such as the moving mass, spark timing, and equivalence ratio to describe their effects on system performance and the feasibility of optimising these parameters for optimal engine performance.

In [2] a model of a Linear Joule Engine driving a simplified linear alternator was presented and used to propose an overall optimised system design. When approached from a thermodynamics perspective, authors tend to simplify the electrical machine to an ideal damper, where the alternator force varies linearly with velocity acting against engine's driving force. In electrical terms, this assumption means the machine inductance is ignored, the electrical load is purely resistive and there is no force ripple. Whilst this may be applicable to a constant velocity generator, where inductance can be tuned out with a capacitive load, the variable velocity operation of the free piston engine gives a variable electrical frequency where no capacitive tuning can be implemented. In addition, a pure damper includes no effects of the combined electromagnetic forces, machine losses, and variation of these parameters to the overall FPE system. These performance parameters and forces need to be considered in modelling the LA in order to account for their effects on the integrated system operation, sensitivity and the resulting efficiency. The effect of cogging force on engine performance was discussed in [9], but system efficiency has not yet been reported.

The system efficiency of this engine can be defined by (1)

$$\eta = \eta_{electical} \times \eta_{electronic} \times \eta_{mechanic} \times \eta_{thermodynamic} \quad (1)$$

In this paper a pure resistive load is assumed and mechanical losses are ignored. The efficiency therefore simplifies to (2).

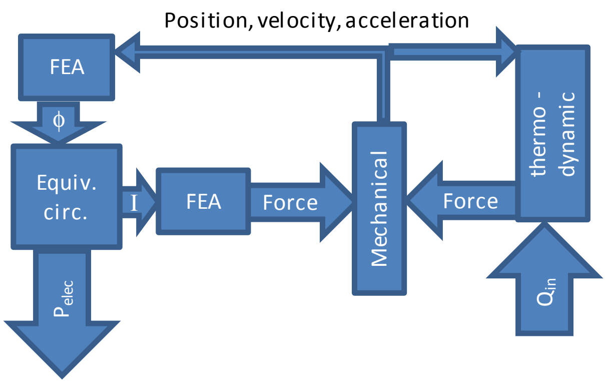

Fig. 4: Schematic of system model

TABLE II. SCALED DESIGN MASSES

Parameter	Translator version		unit
	short	*long*	
Mass of magnet	1.59	3.18	kg
Mass of pole pieces	2.28	4.49	kg
End plates, piston, shaft	1.33	1.33	kg
Total moving mass	5.20	9.00	kg
Copper mass	19.04	9.52	kg
Stator iron mass	14.22	7.18	kg
Total stator	33.26	16.7	kg
Total electrical machine	38.46	25.7	kg

$$\eta = \eta_{electical} \times \eta_{thermodynamic} \tag{2}$$

In an integrated system, the two efficiencies are inter related and both are affected by the electrical machine design. To investigate the effect of translator length, therefore, on system an integrated model is required. The thermodynamics and mechanics of the system can be well represented in LMS AMESim [2]. For the electromagnetic behaviour, however, finite element analysis results were used and transferred into the LMS model via a series of look up tables.

For motor design, it is common to assume the terminal voltage of a machine is fully controlled and hence it is acceptable to fix the current density in the coils as a way of investigating alternative topologies. For a generator, it is conceptually easier to consider the machine feeding a resistive load – and the current in the coils is hence dictated by external resistance. For simplicity, the electrical load of the system in this study was therefore assumed to be a resistive load.

For each of the two designs, load resistance was varied to give either maximum electrical power or maximum system

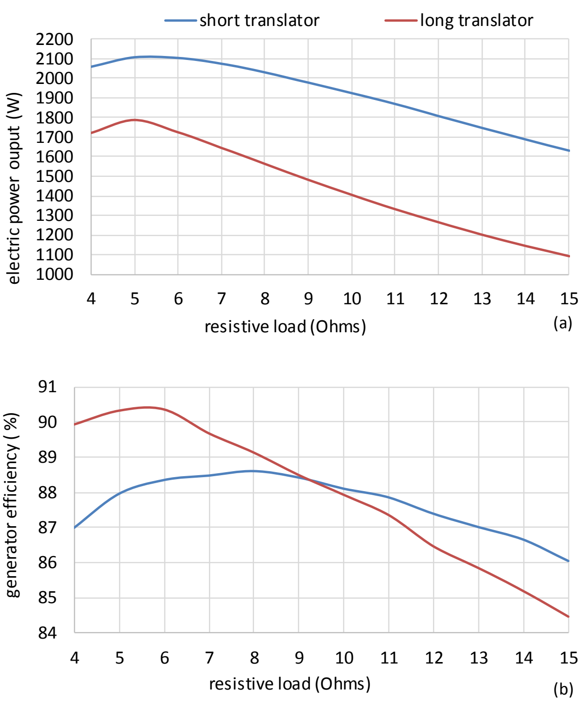

Fig. 5: Comparison of the long (9kg) and short (5.2 kg) translator in terms of (a) power and (b) electrical efficiency.

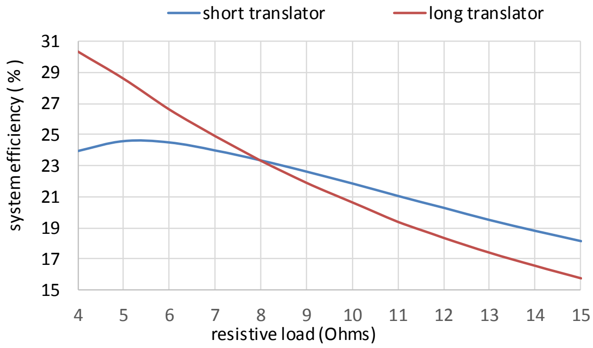

Fig. 6: Comparison of the long (9 kg) and short (5.2 kg) translator in terms of system efficiency.

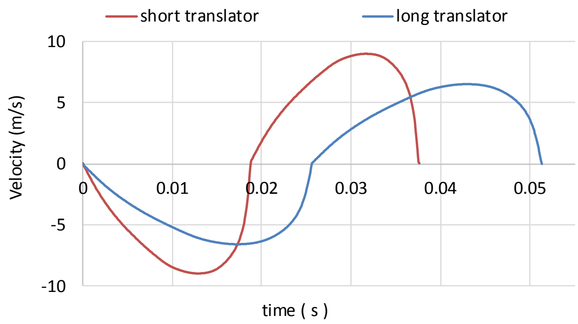

Fig. 7: Engine response at open circuit for the two translators with different mass.

efficiency. A schematic of the model is given in Fig. 4. The back emf is calculated as a function of instantaneous flux change, calculated by finite element analysis look up tables incorporating the velocity and position of the translator. This is fed into a simple equivalent circuit model assuming known internal and external resistance and machine inductance. The resulting current is used in a second finite element analysis derived look up table to give the electromagnetic force. The thermodynamic model includes the heat energy, cylinder position and engine valves, and also outputs an instantaneous force based on position, velocity and heat energy. The two models are coupled together with a mechanical model to calculate instantaneous acceleration at every time step. The result is a fully coupled model where instantaneous heat energy into the system and electrical power out are calculated.

IV. SCALED DESIGN INTEGRATED MODEL

In this first investigation, the electrical design was assumed to be modular, and so the translator length was halved, and the stator length doubled, Fig. 2 and Table II. The obvious side effects of this approach are the doubling of the stator resistance, the almost halving of the translator mass (from 9 kg to 5.2 kg) and doubling of the stator mass. Performance results of this study, obtained from the integrated model, are shown in Fig. 5. The general shape of the electric power verses external resistance curve has a peak (Fig. 5(a)), which is well known to occur when the external and internal impedances are equal. The short translator machine gives a significantly greater power output, and so an initial conclusion could preference the shorter translator. Considering electrical efficiency (Fig. 5(b)), however, the designer might favour the longer translator, as its coils have half the resistance, giving lower copper losses in the generator at peak load. When coupled to a 5 Ohm resistor, the maximum power point for both machines, the long translator model has an efficiency of over 90%, whereas the short translator is 88%.

Of more importance here is the system efficiency, comprising of the electrical power output divided by the heat power input to the system. As shown in Fig. 6, the performance difference between the two machines is greater on a system level (29% efficiency verses 25% at maximum power). This is because the low thermodynamic efficiency of the engine dominates the system and is also dependent on the mass of the translator.

There is an apparent inconsistency here: the electric machine delivering a higher output power is operating with a lower efficiency. In fact, the heat energy going into the system is varying as the engine reacts to the different mover mass – a severe irritation to the electric machine designer when trying to assess machine options. Fig. 7 shows the engine displacement over time from the integrated models of the two machines operating at open circuit. The mechanical frequency of the engine increases with a lower moving mass, and so the heat energy absorbed by the engine increases. The short translator has an input combustion power of approximately 1.3 times that of the long translator. From an electrical perspective, it is not correct to directly compare the machines under these different operating conditions. In some respects, this is a limitation with using a multi-physics model.

V. Fixed Moving Mass Fixed Velocity Design

The dynamic performance of the coupled electrical-thermodynamic system is defined by the four interlinked disciplines shown in Fig. 8. The valve timing, engine geometry and engine controller is beyond the scope of this paper, but have effectively been optimised in their own right [2, 10-12]. At high mechanical frequencies, the force required to accelerate the moving mass is greater than the electromagnetic force reacted by the linear generator. The mass of the electrical machine translator therefore has more influence on the engine operation speed than the variation in electromagnetic force. To a reasonable accuracy, designing the moving mass to be constant between designs effectively constrains the engine to run at the same mechanical frequency – despite a variation in force capability. The rate of using heat energy by the system will be roughly the same for long and

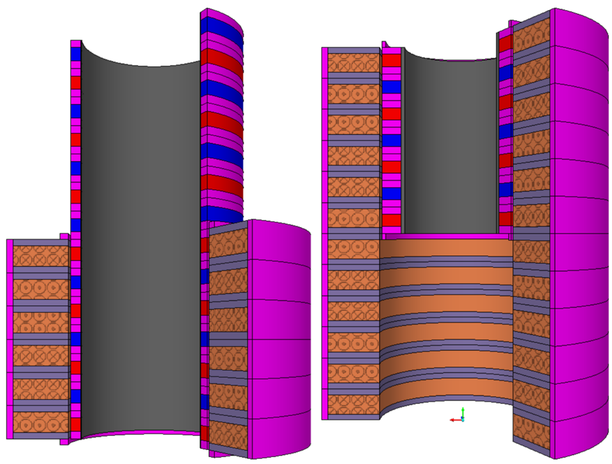

Fig. 9: Long and short translator with same active mass

TABLE III. Fixed Translator Mass Design

Parameter	Translator version		unit
	short	*long*	
Mass of magnet	1.59	1.59	kg
Mass of pole pieces	2.28	2.28	kg
End plates, piston, shaft	1.33	1.33	kg
Total moving mass	5.20	5.2	kg
Copper mass	19.04	9.52	kg
Stator iron mass	14.22	7.18	kg
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Total electrical machine	38.46	21.9	kg

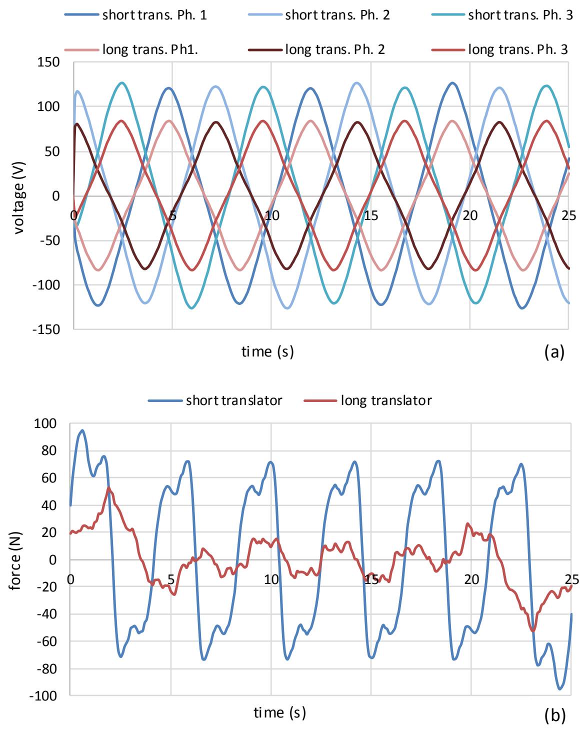

Fig. 10: Comparison of the fixed mass (5.2kg) long and short translators at open circuit at constant velocity of 5 m/s. Back emf (a) and cogging force (b).

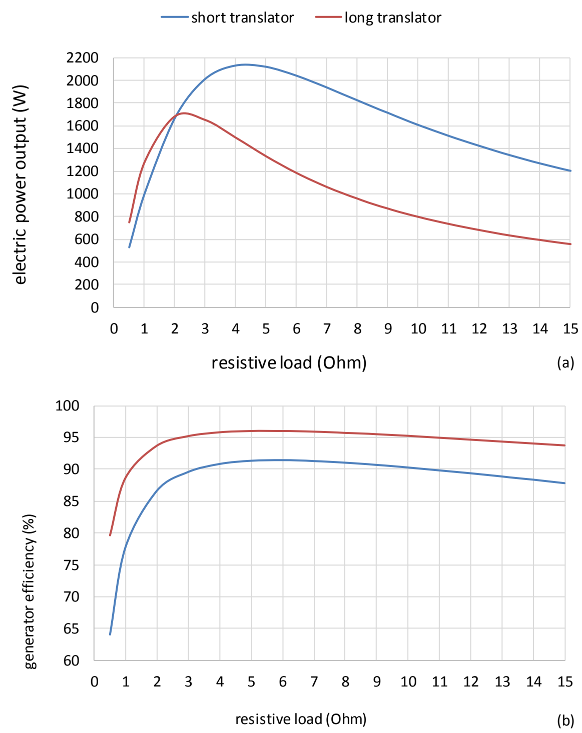

Fig. 11: Comparison of the long (5.2kg) and short (5.2 kg) translator in terms of (a) power and (b) electrical efficiency, at a constant velocity of 5 m/s

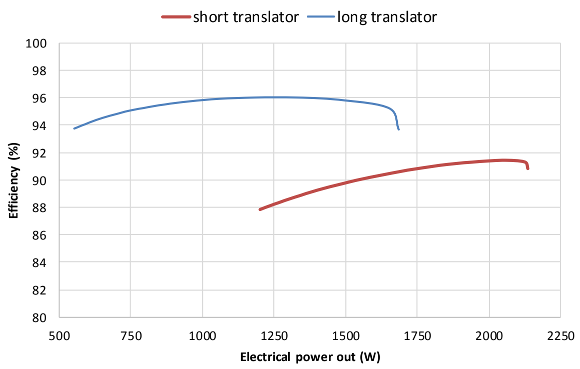

Fig. 12: Electrical efficiency verses electrical power out for the fixed mass (5.2kg) long and short translators at a constant velocity of 5 m/s.

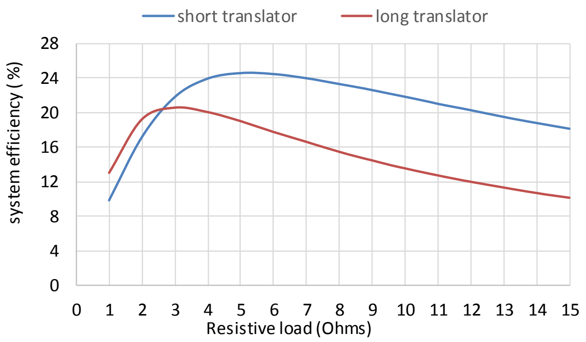

Fig. 13: System efficiency for the fixed mass (5.2kg) long and short translators coupled to the full system model.

short translator models in this scenario and so electrical performance can be compared.

Fixed mechanical frequency implies a fixed peak operation velocity and therefore, to try and isolate the effect of electrical machine translator length, in this section electrical machine performance assuming a fixed peak engine velocity is discussed.

Two translators with a mass of 5.2 kg are shown in Fig. 9 and table III. The mass is fixed by reducing the depth of the magnet and pole pieces in the long translator model. The open circuit simulation results when operating at a constant velocity of 5 m/s are shown in Fig. 10. The shorter translator now consists of deeper magnets and so cogging force and back emf are both seen to increase.

Electrical power and efficiency for the two designs is shown in Fig. 11. Electrical efficiency for the long translator is always larger than the short translator model for fixed values of resistance, however the maximum power output from the short translator model is greater.

As in the previous section, the lower efficiency machine outputs a greater electrical power, meaning that the input mechanical power to the generators is not equal in this scenario. The shorter translator, with its deeper magnets, is electromagnetically a 'better' machine. For example, considering a fixed current of 24 Amps in both machines, the reactive force from the short translator is 1.5 times that of the long version.

Not surprisingly, the graphs assuming a fixed velocity and resistive loading represent different values of mechanical power as the electromagnetic force is not constant. Again, it is perhaps not correct to compare efficiencies of machines operating at different powers. In Fig 12. the data is replotted as efficiency verses electrical power out. This clarifies that although the long translator gives an electrically more efficient design, it cannot match the power output of the short translator design. Using this analysis, the electrical designer appears to have a choice between power density of the combined unit and overall efficiency. This section has ignored the response of the engine to a varying electromagnetic force.

VI. Fixed Mass full integrated model

The designs from section V and shown earlier in Fig. 9 are here used in the full integrated model. The overall system efficiency is shown in Fig. 13. At all but very low values of resistance, the short translator model gives the higher values of system efficiency. Combined with the power output graph of Fig. 11, which showed the short translator gives a higher electrical power output, the overall advantage of the shorter translator model for this application is now clear.

VII. Conclusion

This paper has discussed the influence of the translator length on the performance of a linear generator integrated within a free piston engine. An integrated thermodynamic and electr mechanical model has been presented and three scenarios assessed: doubling translator length, fixing translator mass and velocity and fixing translator mass and integrated performance. Considering the full system performance, the shorter translator generator can give a greater output power and a greater efficiency, albeit with a heavier overall electrical machine.

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